Main Injector Note: 291

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Contents

1 Introduction

The Recycler Ring [1] located in the upper portion of the Main Injector tunnel at Fermilab is designed as a storage ring for antiprotons. Antiprotons transferred from the Accumulator and the residual Tevatron stores will be cooled and stored in the Recycler before reinjection into the Tevatron. The stacking rate of the antiprotons in the Accumulator is improved by steady transfer of antiprotons to the Recycler Ring when the stack size becomes sufficiently large. Thus, as a part of Run II upgrade, the Recycler Ring will provide a factor of 2-3 improvement in luminosity. Pressently, the Recycler Ring (RR) is being commissioned using protons as well as antiprotons. Here we describe the design of the RR vacuum, compute the pressure profile for the residual vacuum gases around the ring and compare with measured partial pressures of residual gases. We estimate the RR beam life time and emittance growth due to the interaction of residual gases with the beam particles. The relevant RR parameters used are listed in Table 1. More detailed description of the Recycler Ring can be found elsewhere [1].

Paramater	**Value**
RR Acceptance (mm-mr)	40.0π
Average β (m)	45.0
Average beam pipe radius (in m)	0.023
Beam energy (GeV)	8.89
Beam energy acceptance	$\pm$ 23 MeV (0.25%)
Average beam particle β	0.998
Average beam particle γ	9.48
Maximum energy loss (GeV)	0.089
Nominal Horizontal tune	25.425
Nominal Vertical tune	24.415

Table 1: The Recycler Ring Parameters

After a brief description of the RR vaccum system in Section II, the residual gases present are listed in Section III. The simulation of pressure profile for each gas is outlined in Section IV and the comparison with RGA measurements is made in Section V. The RR beam life time due to vacuum is estimated and compared with measurements in sections VI and VII respectively.

In Section VIII, the beam emittance growth due to vacuum is computed and compared with measured values. The subsequent sections detail the present status, proposed vacuum upgrades and future plans.

2 The Recycler Ring Vacuum System

The RR vacuum design was motivated by the requirement of storing about 2.5×10^{12} antiprotons with less than 5% loss for stores of duration 8 hours or more. This implies a beam life time of greater than 100 hours and a transverse emittance growth rate less than 2 πmm-mr/hour. In turn, this imposes very stringent requirements on the amount of residual gases allowed in the RR vacuum. Therefore the vacuum design is expected to support only a few tenths of nano Torres of total gas pressure with only a minor amount of heavy gases such as Argon, CO_2 etc..

The RR beam pipe is made up of steel and is mostly elliptical in shape with horizontal major axis 9.67 cm and vertical minor axis 4.44 cm. It also has 3 and 4 inch radii circular portions (for about 7% of the total length) in the straight sections of the ring. There are 614 Titanium Sublimation Pumps (TSP) distributed periodically around the Ring with a distance of 4-5 m between the pumps depending on the location. These were custom designed and built by Fermilab with a pumping speed of 10460 liters/second for Nitrogen. These are fired manually every 6-12 months depending on the gas pressure needs. There are also 115 Ion Pumps (IP) located around the Ring most of them fitted directly to a TSP. The Ion pumps are diode pumps made by Varian [6] with a Nitrogen pumping speed of 30 liters/second. The details of the beam pipe geometry and vacuum pump specifications are provided in Table 2.

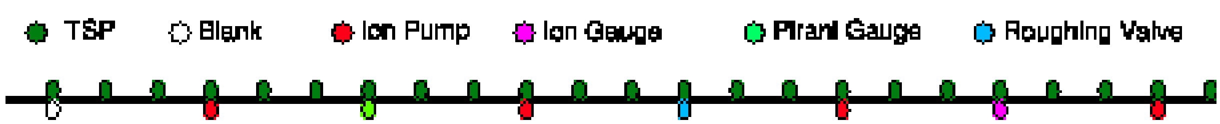

Figure 1: Vacuum pumps configuration in the RR at present

The vacuum pressure is readout and monitored by 30 Ion gauges along with Ion pumps located through out the Ring. There are also 6 Residual Gas Analyzers (RGA) installed at strategic locations providing partial pressures of residual gases present. The schematics of the pump configuration is shown in the figure below. The RR vacuum is also divided into 30 sections separated by control valves that can be closed or opened. This configuration helps to isolate parts of the vacuum when necessary during maintenance, repairs or installation of new devices.

Parameter	Value
Universal Gas Constant (R)	8.3145 J/K mol
Vacuum Temperature (T)	293 K
TSP Pumping Efficiency (TspEff)	0.05
Ion Pump Efficiency (IpEff)	1.0
Ring Length	3319.4
Number of TSPs	615
Number of Ion Pumps	115
Number of Ion Gauges	30
Number of Vacuum Sectors	30
Number of RGAs	6
Elliptical Sections	[MKS Units]
Major axis (b) [m]	9.667×10^{-2}
Minor axis (a) [m]	4.444×10^{-2}
Area of the Pipe (EA) [m^2]	33.741×10^{-4}
Circumference (EC) [m]	0.23×10^{-2}
Area of TSP Aperture (ATsp) [m^2]	34.90×10^{-4}
Area of Ion Pump Aperture (AIp) [m^2]	28.60×10^{-4}
Length of Ion Pump (Ipl) [m]	6.033×10^{-2}
Diameter of 3' Beam Pipe (Bp3D) [m]	7.303×10^{-2}
Area of 3' Beam Pipe (Bp3A) [m^2]	41.883×10^{-4}
Perimeter of 3' Beam Pipe (Bp3C) [m]	22.9415×10^{-2}
Diameter of 4' Beam Pipe (Bp4D) [m]	9.8425×10^{-2}
Area of 4' Beam Pipe (Bp4A) [m^2]	76.085×10^{-4}
Perimeter of 4' Beam Pipe (Bp4C) [m]	30.9211×10^{-2}

Table 2: Beam pipe geometry and vacuum pump specifications for RR

3 RR Vacuum Residual Gases

The RR ultra high vacuum maintained by arrays of TSPs and Ion pumps has a total pressure of a fraction of a nano Torres. The types of gases present in the vacuum and their partial pressures can be obtained by RGA readings monitored regularly. The major constitutents of the vacuum are listed below. We have also detected some very minor quantities of hydro carbons such as Ethane, Etheylene etc. The observed gases and the relevant parameters are listed in Tables 3 and 4.

Gas	**Content** [%]	**Avg. Pres.** [Torr]
H_2	67.22	4.9E-11
H_2O	21.13	1.8E-11
CO	3.36	1.7E-12
Ar	0.02	8.9E-12
CH_4	0.85	2.4E-11
CO_2	6.53	3.8E-12
$Unknwon$	0.89	4.5E-13
Total	100.00	1.1E-10

Table 3: RR Vacuum Gas Composition

Gas	Molar Mass M [grams/mol]	Pumping Speed s [liter/s]	Outgassing Rate q [(nTorr.liter)/(s m^2)]	Aperture Constant $K_a = \sqrt{RT/2\pi M}$
H_2	2.016	3490.000	7.000E-08	43.786
H_2O	18.016	3490.000	2.200E-08	14.647
CO	28.010	10460.000	3.500E-09	11.747
CO_2	44.010	8775.000	6.800E-09	9.371
CH_4	16.042	30.000	8.800E-10	15.522
N_2	28.013	10460.000	3.500E-10	11.746
Ar	39.948	1.70	2.100E-11	9.836

Table 4: The relevant gas parameters required for simulation of the pressure profile around the ring. The outgassing rates are obtained from test stands. The 'unknown gases' are treated as Nitrogen.

4 Pressure Profile Simulations

Knowing the complete beam pipe geometry, the vacuum pump configuration and the details of gas parameters such as outgassing rates, conductances etc., we can simulate the pressure profile of each gas around the ring. For simulation purposes, we treat the 'unknown' component as Nitrogen. The Ion Pumps mostly pump Argon and Methane as their pumping power of other gases such as Hydrogen, Water, Carbon Monoxide, Carbon Dioxide and Nitrogen is negligible. The TSPs do not contribute to pumping out Argon or Methane also.

The vacuum pressure P, the pumping speed s, the conductance of the beam pipe c and the outgassing rate q at a given location are related by:

$$\frac{d}{dz}\left\{c\frac{dP}{dz}\right\} - sP + q = 0$$

A technique based on the approximation of *finite differences* is used to solve the above differential equation [7]. This method has the advantage of being numerically stable when the system is very long such as the Recycler Ring. We cast the first term as:

$$\frac{d}{dz}\left\{c_i\frac{dP}{dz}\right\} = \frac{(c_{i+1}+c_i)P_{i+1} + (c_I + c_{i-1})P_{i-1} - (c_{i+1}+c_{i-1}+2c_i)P_i}{2\Delta z^2}$$

The above equation becomes:

$$\frac{c_i + c_{i-1}}{2}P_{i-1} + \left\{\frac{-(c_{i+1}+c_{i-1}+2c_i)}{2} - s_i\Delta z^2\right\}P_i + \frac{c_i+c_{i+1}}{2}P_{i+1} = -q_i\Delta z^2$$

The boundary conditions at each end of the segment should be specified:

$$Q_i = -c_i\frac{P_{I+1} - P_{i-1}}{2\Delta z}$$

This allows us to solve for either P_{i+1} or P_{i-1} in terms of the flow in the ith segment. In fact we can form a tridiagonal matrix:

$$\left\{\begin{array}{cccccc} -\frac{c_2+3c_1}{2} - s_1\Delta z^2 & \frac{c_2+3c_1}{2} & & & & \\ \cdot & \cdot & \cdot & & & \\ & & \frac{c_i+c_{i-1}}{2} & -\frac{c_{i+1}+c_{i-1}+2c_i}{2} - s_i\Delta z^2 & \frac{c_{i+1}+c_i}{2} & \frac{c_{i+1}+c_i}{2} \\ & & & \cdot & \cdot & \cdot \\ & & & & \frac{c_{n-1}+3c_n}{2} & -\frac{c_{n-1}+3c_n}{2} - s_n\Delta z^2 \end{array}\right\}\left\{\begin{array}{c} P_1 \\ \cdot \\ P_i \\ \cdot \\ P_n \end{array}\right\} = \left\{\begin{array}{c} -q_1\Delta z^2 - 2Q_1\Delta z \\ \cdot \\ -q_i\Delta z^2 \\ \cdot \\ -q_n\Delta z^2 - 2Q_n\Delta z \end{array}\right\}$$

The above system of equations can be solved by Gaussian elimination technique and back substitution. A simpler alternative approach for an array of regular periodic pumps is given in the Appendix.

For each gas contitutent gas, the pressure profile around the ring has been simulated. The results for Hydrogen and Methane are shown in Figures 2 and 3 for region in the 400 section of the RR. Note the Hydrogen is pumped by the TSPs and Methane by the Ion pumps. The x-axis of these figures are location of various sectors from the point of proton injection into the Recycler at the location 328 in units of meters. The TSPs and Ion Pump locations are also shown along with beam pipe gemetry. The Ring wide average pressure and the average of the region shown by the plot are also listed. The sector pressure averages are graphically illustrated in Figures 4 and 5 for various gases. The RR simulated gas pressure averages are listed in Table 5.

Gas	Avg. Pressure (nTorr)
Hydrogen	0.811
Water	0.240
Carbon Monoxide	0.037
Carbon Dioxide	0.091
Nitrogen	0.010
Argon	0.047
Methane	0.310
Total	1.546

Table 5: The Ring wide average of the simulated pressure of residual gases.

(Description of sector average plots will be given after final plots!)

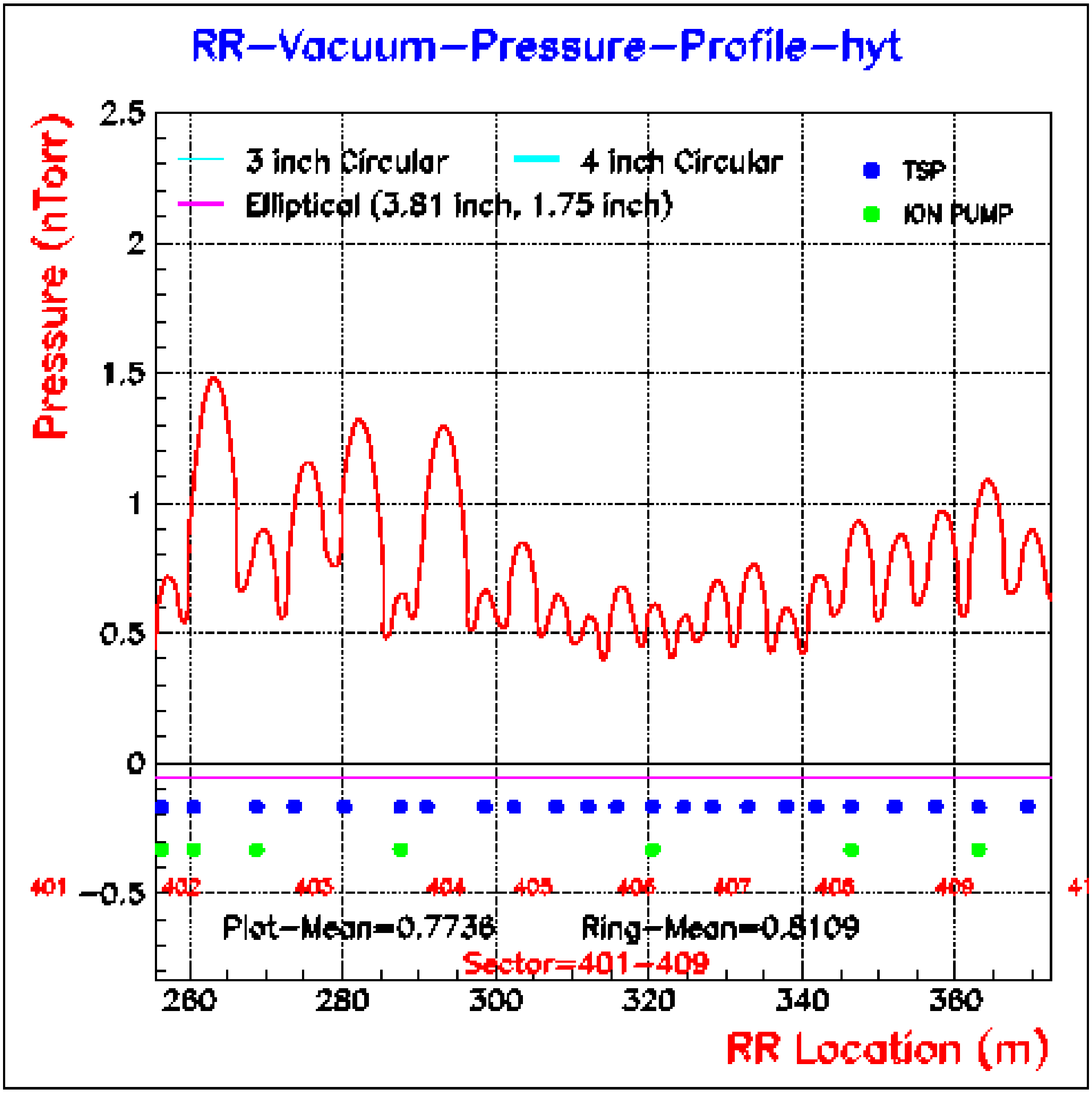

Figure 2: Pressure profile for Hydrogen in the 400 region of the RR. Note the hydrogen is pumped by TSPs and the contribution of Ion pumps is negligible

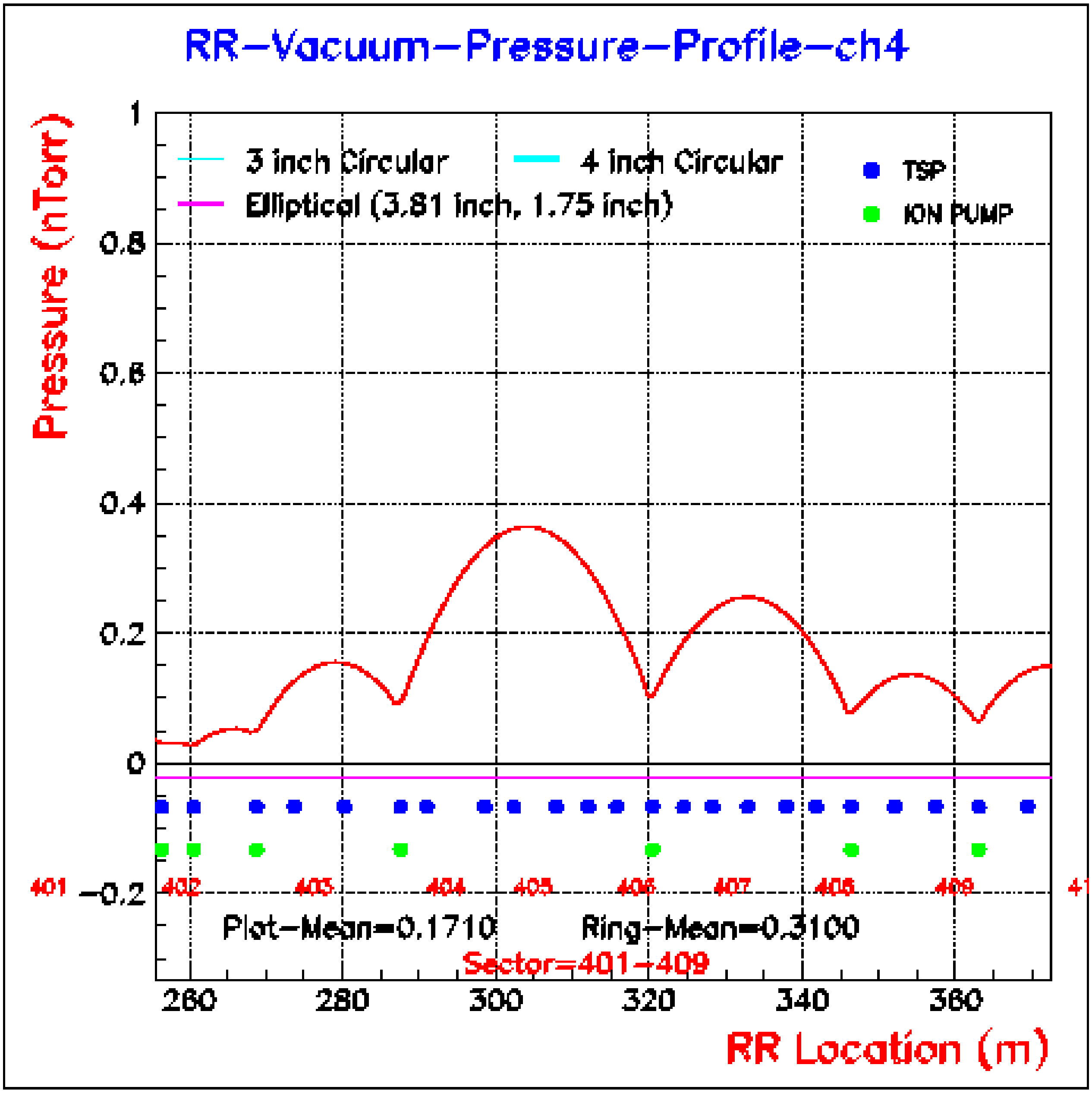

Figure 3: Pressure profile for Methane in the 400 region of the RR. Note the hydrogen is pumped by Ion Pumps and the contribution of TSPs is negligible

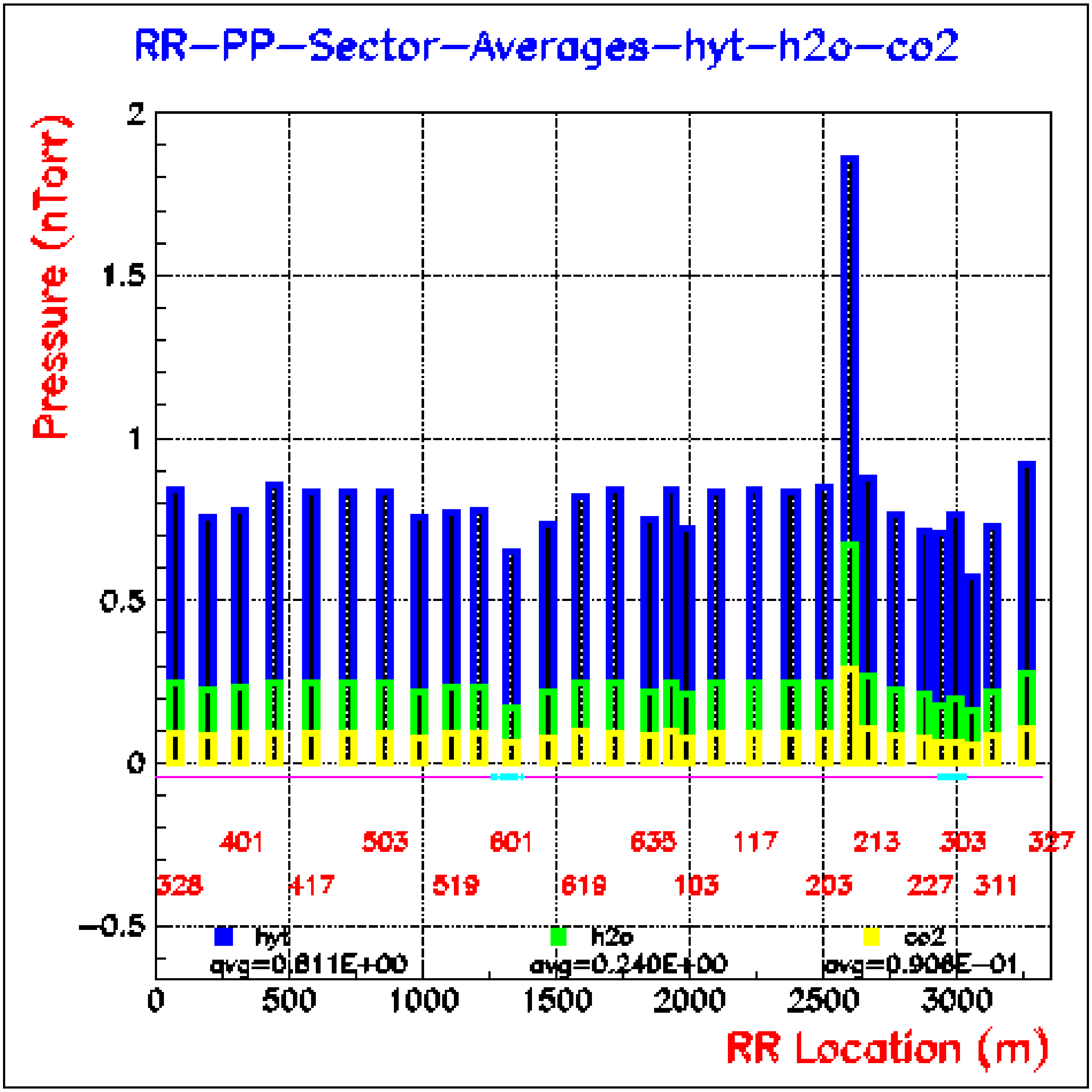

Figure 4: Pressure profile sector averages for Hydrogen, Water and Carbon Dioxide around the RR.

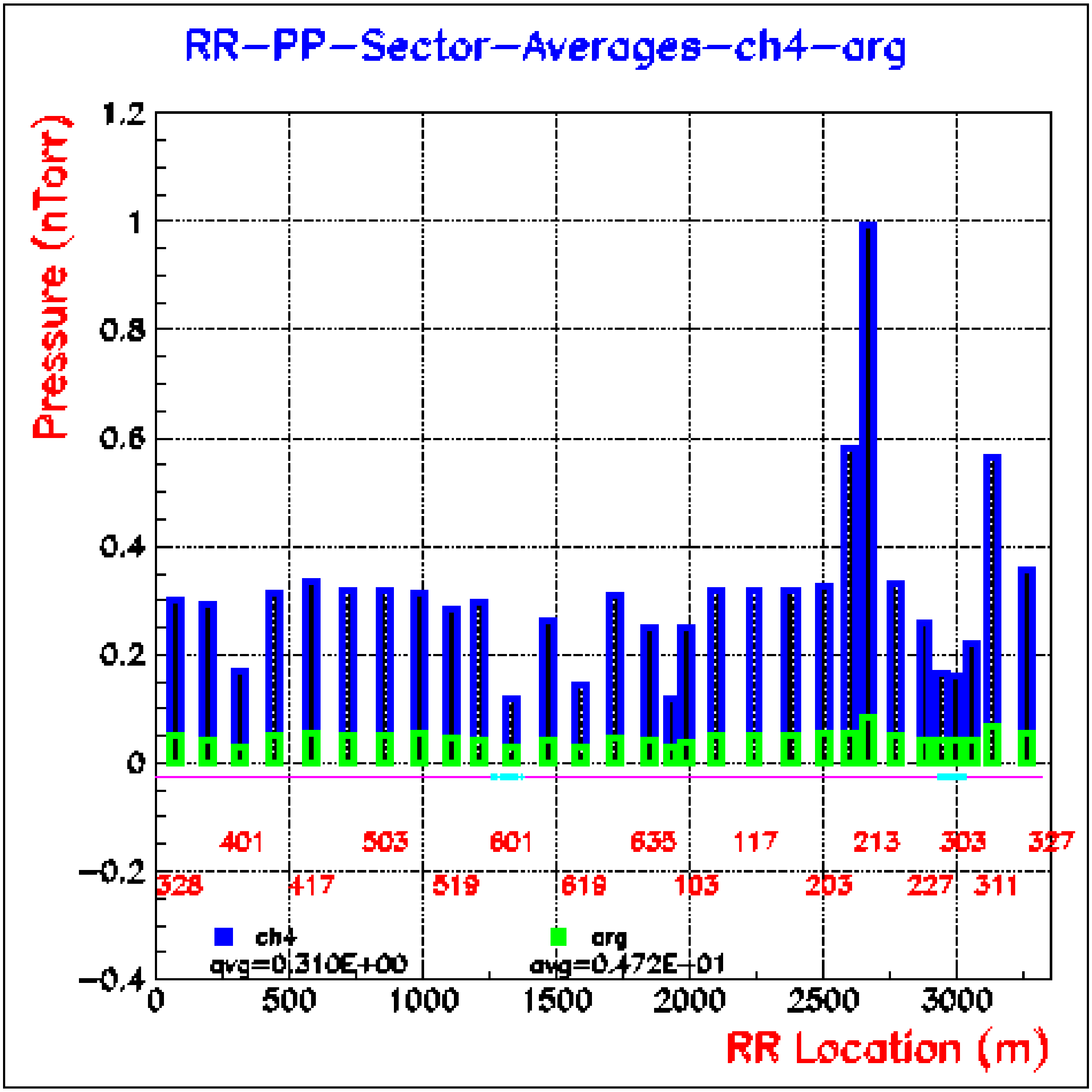

Figure 5: Pressure profile sector averages for Argon and Methane around the RR.

5 Comparison with RGA Meaurements

Here we make an attempt to compare the simulated partial pressures of residual gases with those measured from RGA at selected locations in the Recycler Ring. There are many inherent uncetainities we need to take into account: details of vacuum geometry, outgassing rate for each residual gas as well as uncertainities associated with RGA measurements at nano Torre pressure levels. The following RGA measurements shown in the following tables are average of 3 readings taken during the past 1 year.

RGA	Measurement [nTorr]	Simulation [nTorr]	Ratio [Meas./Simul.]
RGA305-H_2	1.200	0.349	3.439
RGA305-H_2O	0.130	0.070	1.863
RGA305-CO_1	0.019	0.007	2.467
RGA305-CO_2	0.016	0.018	0.891
RGA305-Ar	0.130	0.043	3.030
RGA305-CH_4	0.047	0.173	0.272
RGA305-Total	1.562	0.662	2.359

RGA	Measurement [nTorr]	Simulation [nTorr]	Ratio [Meas./Simul.]
RGA602-H_2	1.000	0.650	1.537
RGA602-H_2O	0.150	0.174	0.864
RGA602-CO_1	0.045	0.025	1.805
RGA602-CO_2	0.070	0.060	1.160
RGA602-Ar	0.020	0.028	0.710
RGA602-CH_4	0.030	0.093	0.322
RGA602-Total	0.940	1.037	0.906

The measured values on the average are roughly with in a factor of 2 of the simulated values. Further improvements can be mnade by adjusting the outgassing rate for each residual gas separately.

6 Life Time Estimation

Here, we estimate the beam life time due to interaction of beam particles (protons) with the prevalent gases inside the beam pipe via coloumb scattering, electronic excitations, bramstrahlung, nuclear scattering and multiple coloumb scattering. The injected beam is assumed to be Gaussian:

$$f(Z) = \frac{a^2}{2\sigma^2} e^{-}(a^2/2\sigma^2)Z$$

with $Z = \epsilon/\epsilon_a$ ranging from 0.0 to 1.0. With an initial beam of 10π mm-mr, $\sigma = 11.53 \times 10^{-3}$m-r. Here ϵ, ϵ_a denotes emittance and Recyler acceptance respectively and a is the half aperture equal to the average radius of the beam pipe (0.023 m).

At any given location s in the ring, the beam life time due to beam-gas interactions is a function of gas densities as well as the β at that location:

$$\tau_{bg}(s) = \tau_{bg}(n_{gases}(s), \beta(s))$$

To obtain the mean life time, we average over the ring:

$$\tau_{bg} = \frac{\int_{ring} ds\ \tau_{bg}(n_{gases}(s), \beta(s))}{\int_{ring} ds}$$

In reality, the above integration is achieved numerically. Below, we discuss each contributing process separately.

6.1 Single Coloumb Scattering

It is possible by a single coloumb scattering off a residual gas nucleus, a proton from the beam can be lost. To estimate the rate of loss by this mechanism, we use the classic Rutherford scattering formula [2].

$$\frac{1}{\tau_{sc}} = \frac{-1}{N}\frac{dN}{dt} = \beta c \sum \sigma_j n_j$$

where the sum is over the species of residual gas molecules with density n_j and σ_j is given by:

$$\sigma_j = \frac{4\pi Z_j^2 r_p^2}{\beta^4 \gamma^2 \theta_{max}^2}$$

with Z_j, the atomic number of jth gas and θ_{max} denoting the maximum angle deflection needed for knocking of the proton. For a particle at the center of the beam pipe, the angle θ_{max0} is by:

$$\theta_{max0} = \sqrt{\frac{Acceptance}{\pi \beta_{avg}}}$$

Now for a particle located away from the center, we need to modify the above expression. For particle with x and x' as the transverse coordinates, we know:

$$\gamma x^2 + 2\alpha x x' + \beta x'^2 = A^2$$

where α, β, γ and A are the Courant-Snyder parameters and admittance respectively. Note A^2 is actually acceptance in units of π. Now using $\gamma = \frac{1+\alpha^2}{\beta}$ and solving for x':

$$x' = \frac{-x\alpha \pm \sqrt{A^2\beta - x^2}}{\beta}$$

The quantity in the square root can be expanded in terms of $\frac{x^2}{A^2\beta}$ and we obtain after omitting higher order terms:

$$x' = -\frac{x\alpha}{\beta} \pm \frac{A}{\beta^{1/2}} \mp \frac{x^2}{2A\beta^{3/2}} \mp \frac{x^4}{4A^3\beta^{5/2}}$$

Assuming a Gaussian form G(x) for the beam shape, we can get a better approximation of the maximum scattering angle. Now averaging over the beam distribution,

$$\int dx x G(x) = 0.0$$

$$\int dx x^2 G(x) = \frac{\sigma^2}{2}$$

$$\int dx x^4 G(x) = \frac{3\sigma^4}{4}$$

$$< x' >= \pm[\frac{A}{\beta^{1/2}} - \frac{\sigma^2}{4A\beta^{3/2}} - - \frac{3\sigma^4}{16A^3\beta 5/2}] = \pm\frac{A}{\beta^{1/2}}[1 - \frac{1}{4}(\frac{\sigma}{A\beta^{1/2}})^2 - \frac{3}{16}(\frac{\sigma}{A\beta^{1/2}})^4]$$

Therefore, the beam life time due to single coloumb scattering can be cast as usual:

$$\frac{1}{\tau_{sc}} = \frac{4\pi r_p^2 c}{\beta^3\gamma^2 < \theta_{max} >^2} \sum Z_j^2 n_j$$

6.2 Inelastic Scattering:

There are two important processes in the inelastic scattering: (a) Bremsstrahlung scattering where the proton emits a photon and the nucleus of the gas atom is left unexcited (b) Inelastic scattering (excitation) of the electrons of the atoms from momentum transfer. We examine each case below.

The total cross section for the bremstrahlung can be written for a given gas as [3]:

$$\sigma_{br} = \int_{\epsilon_m}^{E} \{\frac{d\sigma}{d\epsilon}\} d\epsilon$$

where E denotes the energy of the proton, ϵ_m the photon energy and

$$(\frac{d\sigma}{d\epsilon})_{br} = \frac{4\alpha Z^2 r_p^2}{\epsilon}\{[\frac{4}{3}(1-\frac{\epsilon}{E}) + \frac{\epsilon^2}{E^2}][\frac{\phi_1(0)}{4} - \frac{1}{3}\mathrm{InZ}] + [\frac{1}{9}(1-\frac{\epsilon}{E})]\}$$

with $\phi_1(0)$ representing the screening function. A similar expression applies to the case of atomic/molecular electron excitations:

$$(\frac{d\sigma}{d\epsilon})_{ee} = \frac{4\alpha Z r_e^2}{\epsilon}\{[\frac{4}{3}(1-\frac{\epsilon}{E}) + \frac{\epsilon^2}{E^2}][\frac{\psi_1(0)}{4} - \frac{2}{3}\mathrm{InZ}] + [\frac{1}{9}(1-\frac{\epsilon}{E})]\}$$

Here $\psi_1(0)$ denotes the screening function as $\phi_1(0)$. They can be approximated by $\psi_1(0) \simeq 28.34$ and $\phi_1(0) \simeq 20.836$.

For $\epsilon_m \ll$ E, the above expressions can be evaluated and can be cast as:

$$\sigma_{br} = 4\alpha\{\frac{4}{3}Z^2 r_p^2 \mathrm{In}\frac{183}{Z^{1/3}}[\mathrm{In}(E/\epsilon_m) - (5/8)] + \frac{1}{9}(Z^2 r_p^2)[\mathrm{In}(E/\epsilon_m) - 1]\}$$

$$\sigma_{ee} = 4\alpha\{\frac{4}{3}Z r_e^2 \mathrm{In}\frac{1194}{Z^{2/3}}[\mathrm{In}(E/\epsilon_m) - (5/8)] + \frac{1}{9}(Z r_e^2)[\mathrm{In}(E/\epsilon_m) - 1]\}$$

The total cross section is then:

$$\sigma_{br+ee} = \sigma_{br} + \sigma_{ee}$$

The σ_{br} is quite negligible compared to σ_{ee} and therefore we drop it from further consideration. The life time due to inelastic scattering τ_{in} becomes as before:

$$\frac{1}{\tau_{in}} = \frac{-1}{N}\frac{dN}{dt} = \beta c \sum \sigma_{eej} n_j$$

6.3 Multiple Coloumb Scattering:

Unlike the previous two cases, the mutiple coloumb scattering causes emittance growth of the beam. As a result, protons are lost via diffusion across the boundary of the allowed particle distribution in the beam pipe. Therefore we should approach this problem by solving the diffusion equation [4] for a particle distribution f:

$$\frac{\partial f}{\partial \tau} = \frac{\partial}{\partial Z}(Z\frac{\partial f}{\partial Z})$$

subject to the boundary conditions:

$$f(Z,0) = f_0(Z)$$

$$f(1,\tau) = 0$$

where Z $= \epsilon/\epsilon_a =$ emittance/acceptance, and $\tau =$ tR$/\epsilon_a$ with R, the diffusion coefficient. The diffusion coefficient R is given in terms of scattering angle θ by:

$$R = \beta_{avg}\langle\dot{\theta}^2\rangle$$

The general solution of the above equation can be written as:

$$f(Z,\tau) = \sum_n C_n J_0(\lambda_n\sqrt{Z})e^{-\lambda_n^2\tau/4}$$

with coefficients C_n:

$$C_n = \frac{1}{J_1(\lambda_n)^2}\int_0^1 f_0(Z) J_0(\lambda_n \sqrt{Z}) dZ$$

where λ_n is nth root of the Bessel function $J_0(Z)$. Now we can obtain the total beam particles as a function of time:

$$N(\tau) = \int_0^1 f(Z,\tau) dZ = 2\sum_n \frac{C_n}{\lambda_n} J_1(\lambda_n) e^{-\lambda_n^2 \tau/4}$$

The life time due to multiple coloumb scattering can be now computed using the standard expression:

$$\tau_{mc} = -\frac{N(\tau)}{dN(\tau)/d\tau}$$

The beam life time varies with time and normally reaches an asymptotic value:

$$\tau_a = \frac{4\epsilon_a}{\lambda_1^2 R}$$

.

To compute $<\dot{\theta}^2>$, we use the small angle limit of the Rutherford scattering cross section, parametrization of atomic and nuclear radii:

$$<\dot{\theta}^2> = \frac{8\pi r_p^2 c}{\gamma^2 \beta^3}\sum_j n_j Z_j^2 \text{In}[\frac{38360}{(A_j Z_j)^{1/3}}]$$

with A_j denoting the atomic weight of jth gas component.

6.4 Nuclear Scattering:

Here we estimate the beam life time due to the loss of protons from interaction with nucleus of residual gas molecules via strong force. As there is no simple expression for the interaction cross section for the strong force, we use the general formula:

$$\frac{1}{\tau_{nu}} = \frac{-1}{N}\frac{dN}{dt} = \beta c \sum \sigma_j n_j$$

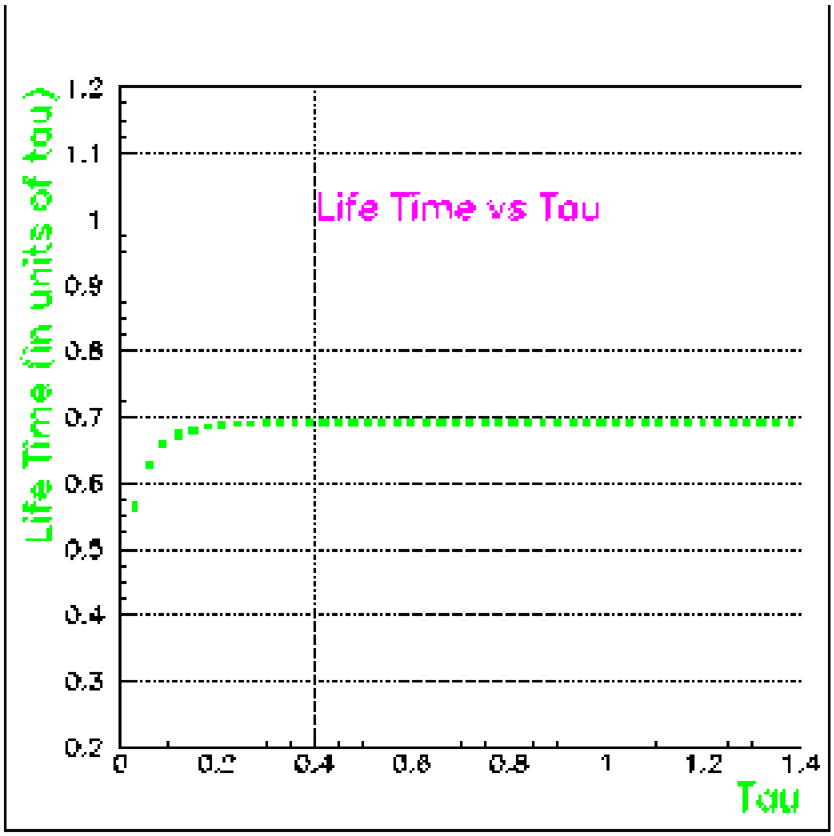

Figure 6: The life time as a function of $\tau = tR/\epsilon_a$ due to multiple coloumb scattering process. The life time reaches an asymptotic value after rising in this case.

where σ_j denotes the total (elastic + inelastic + quasi-elastic) proton-nucleus cross for each gas in the proton relevant energy range. The total cross sections are [5]: $\sigma_{nc}(H) = 40$mb, $\sigma_{nc}(N) = 387$mb, $\sigma_{nc}(C) = 344$ mb, and $\sigma_{nc}(O) =$ 429mb.

6.5 Final Beam-Gas Life Time:

Now we can combine the contributions from various beam-gas interactions to obtain the life time as:

$$\frac{1}{\tau_{bg}} = \frac{1}{\tau_{sc}} + \frac{1}{\tau_{in}} + \frac{1}{\tau_{mc}} + \frac{1}{\tau_{nu}}$$

Using the asymptotic life time for the multiple coloumb scattering, direct evaluation gives the total beam life time due to beam-gas interactions.

Now using the above formalism, we can predict the beam life time using the simulated residual gas pressure profiles in the previously. We do that in two different cases: (a) For gas densities, use the ring averaged pressure densities for computing the final life time; (b) compute the life time around the ring and get a mean final life time (averaged over beta and gas densities simultaneously). The results are tabulated in Table 6.

Physical Process	Using Avg. Pressure [hours]	Ring Avg. Life Time [hours]
Single Coloumb	1.08×10^2	1.05×10^2
Inelastic Scatt.	2.62×10^2	2.58×10^2
Mult. Coloumb	1.32×10^1	1.28×10^1
Nuclear Scatt.	5.80×10^2	5.70×10^2
Total life time	1.10×10^1	1.06×10^1

Table 6: The total life time summary using average pressure and ring averaged life time cases considered.

7 Life Time Measurement

The beam life time in the Recycler Ring depends on many factors such as aperture, size of the input beam, RR tunes, injection mismatch and noise level as well as residual vacuum beam-gas interactions. The effect of aperture and injection mismtach can be eliminated some what by injecting a thin beam and starting the life time measurements after a brief period. At the beginning of the measurement, the beam life time will be dominated by single Coloumb scattering process while the inelastic and scattering nuclear scattering will also contribute. When the beam grows and reaches the aperture limit, the multiple scattering process will be dominant. Relatively, we can make a clear comparison of measured life time in the early stages with the one estimated using the single Coloumb, inelastic and nuclear scattering process only.

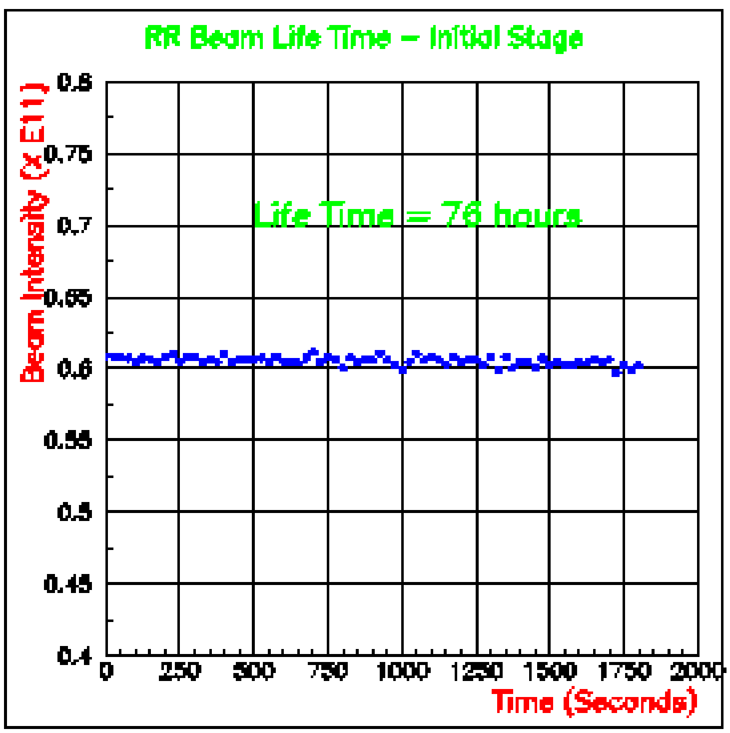

Figure 7: The beam intensity for 30 minutes duration with RR nominal tunes ($\epsilon_x = 0.436$, $\epsilon_y = 0.441$) for a thin beam (scrapped)

In Figure 7, a typical life time measurement is shown. The RR beam intensity is shown for a thin beam for a duration of 30 minutes a few minutes after the injection. Normally it takes about 45-60 minutes for the beam to grow and reach the limits of aperture where the dominant beam mechanism of beam loss is multiple Coloumb scattering.

8 Emittance Growth in the Recycler Ring

We estimate the beam emittance growth due to multiple coloumb scattering of the beam particles (protons) with the residual gas atoms present in the beam pipe. The emittance growth is obtained by:

$$\frac{d\epsilon_N}{dt} = \frac{\pi\beta\gamma}{2}\beta_{avg} < \dot{\theta}^2 >$$

Like life time, we obtain the ring average of emittance growth as:

$$\frac{\epsilon_N}{dt} = \frac{\int_{ring} ds\ \frac{\epsilon_N}{dt}(n_{gases}(s), \beta(s))}{\int_{ring} ds}$$

Using the simulated pressure profile for the vacuum residual gases, we can estimate the emittance growth. The results are summarized in Table 7. The measured values of 95% emittance growth rate in the vertical and horizontal planes in the range of 5-10 πmm-mr/hour.

Quantity	Using Avg. Pressure [πmm-mr/hour]	Ring Avg. Emittance [πmm-mr/hour]
Rms Emittance Growth	3.13	3.05
95% Emittance Growth	18.78	18.30

Table 7: The emittance growth summary using average pressure and ring averaged emittance cases considered.

(Plots and more details will be provided after a few more fresh measurements in the next 2-3 weeks)

9 Vacuum Improvements

As the life time and emittance growth measurements indicate, the RR life time should be improved to meet the challenges of the Run II luminosity goals [8]. This also requires steps to improve the RR life time by a factor of 3. As evidenced in Section 6, the heavy molecules such as Argon, Water, CO_2 contribute much to the life time. Therefore, the amount of residual heavy species have to be brought down. Here, we propose a 3 point strategy to increase the RR life time by a factor 3.

As a first step, the number of Ion pumps present in the Recycler Ring have to be doubled. As pump ports are available, this can be accomplished in a straight forward manner. Then the new configuration of the vacuum pumps is shown in figure 8 as opposed to the old one in Figure 1. Doubling Ion pumps will bring down Argon by a factor of 2 and Methane by a factor of 3. By fixing air leaks and baking well at higher temperatures will help to reduce the water content as well. The estimated RR life times in each of the suggested steps progressively is shown in Table 6.5.

Scenario	**Expected Result**	**Tot. Life Time** [Hours]	**Single Scatt.** [Hours]	**Inel. Scatt.** [Hours]	**Nucl. Scatt.** [Hours]	**Mult. Scatt.** [Hours]
Normal Case	Avg. RGA data	11.4	108.8	291.1	726.2	13.6
Double IPs	Argon X (1/2) CH_4 X (1/3)	15.8	153.5	362.6	861.8	18.9
Fix leaks	Argon X (1/2.5)	20.1.	200.1	415.5	946.6	24.2
Bake well	Water X (1/10)	30.0	300.6	556.1	1339.7	36.4

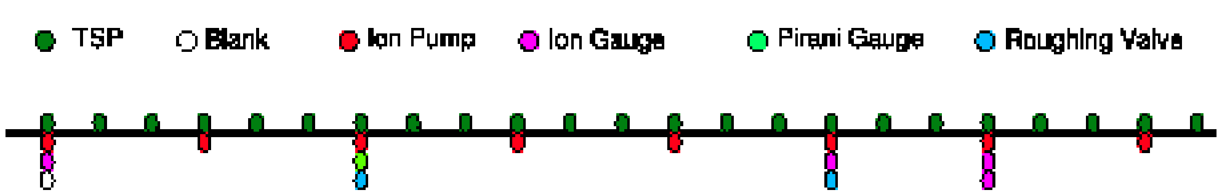

Figure 8: The proposed vacuum pump configuration after doubling Ion pumps at the Recycler Ring.

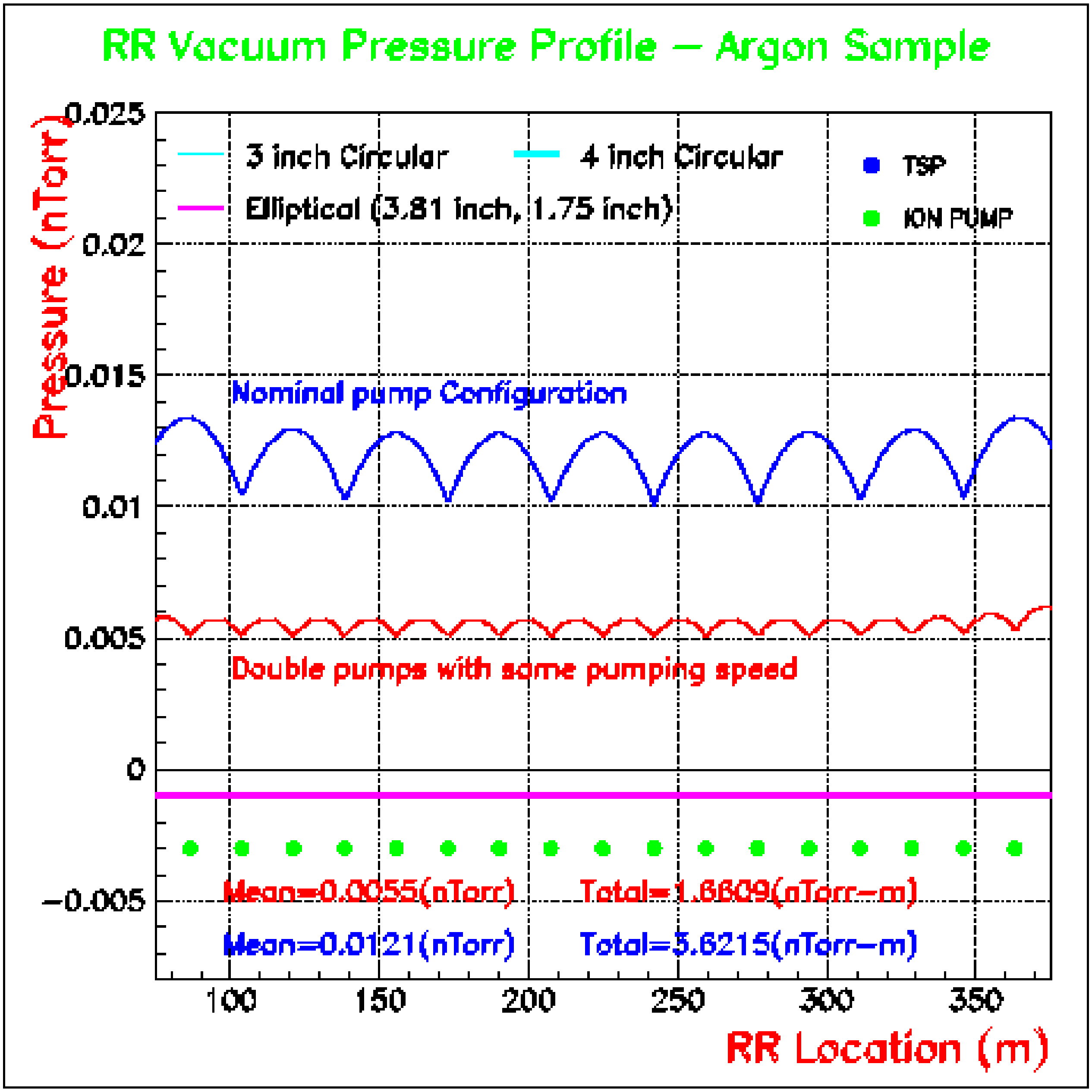

Figure 9: The effect of doubling Ion pumps on the pressure profile of Argon for a typical section in the RR.

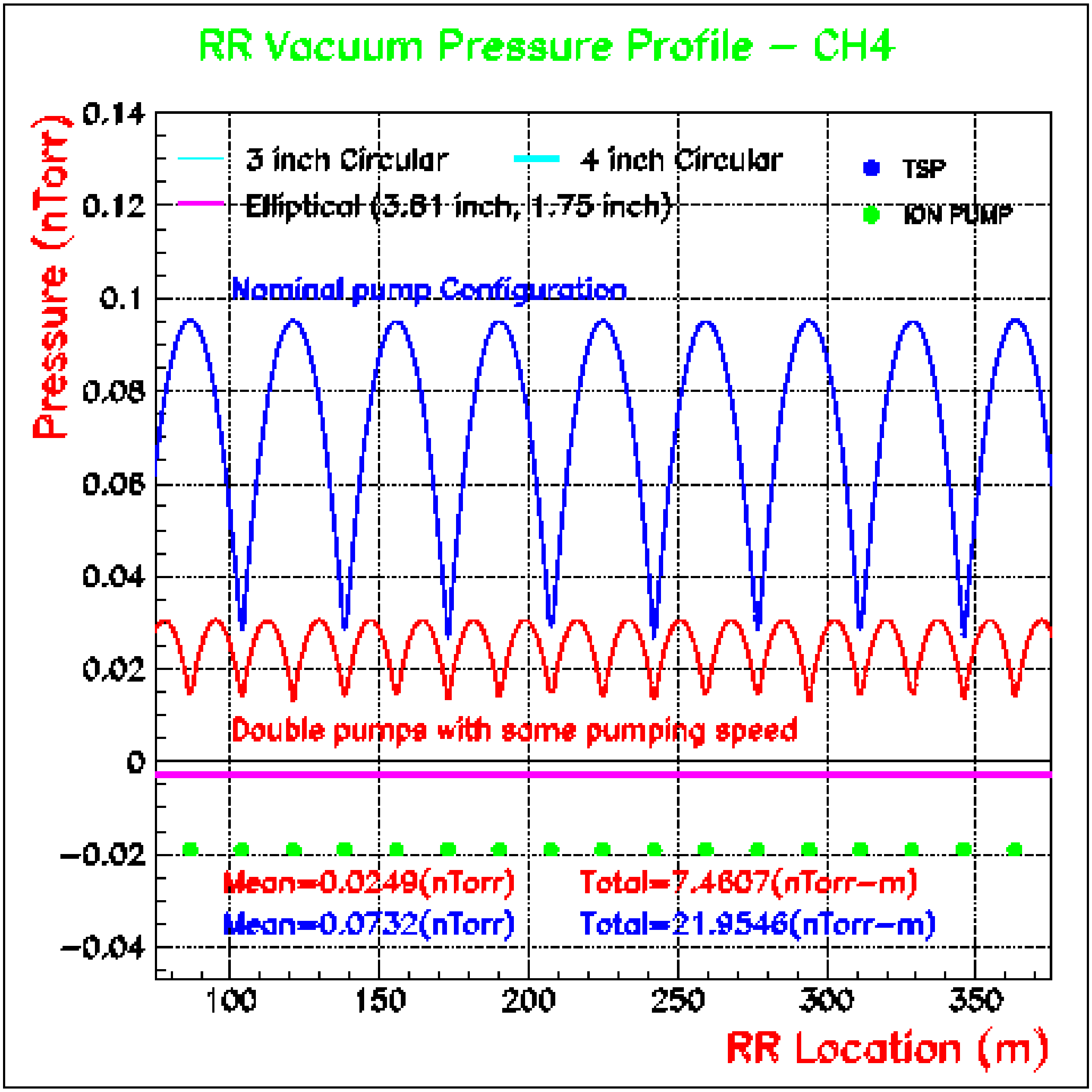

Figure 10: The effect of doubling Ion pumps on the pressure profile of Methane for a typical section in the RR.

10 Summary and Outlook

We have made an attempt to simulate the pressure profile of residual vacuum gases in the Recycler Ring from fiest principles using detailed beam pipe geometry and the necessary gas parameters. We have used these profiles to compute the beam life time due to beam-gas interactions and emittance growth in the transverse plane. We have also compared the estimated values of gas pressures, life time and emittance growth with actual measure values. They seem to agree with in a factor of X as there are much uncertainities in the measured quantities. The proposed improvements for the Recycler vacuum such as doubling of Ion pumps, baking longer at high temperatures are already being implemented now. We expect the Recycler to be fully commissioned and become an integral part of the Fermilab Accelerator complex in the next 6-12 months.

11 Acknowledgements

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References

[1] Gerry Jackson, "The Fermilab Recycler Ring Technical Design Report", November 1996, Fermilab-TM-1991.

[2] A. G. Ruggiero, Fermilab Pbar Note 54, November, 1979.

[3] A. Wurlich in "CERN Accelerator School 1994", CERN-94-01.

[4] D. Edwards and M. Syphers, "An Introduction to Physics of High Energy Accelerators", John Wiley and Sons, 1993.

[5] N. Mokhov and V. Balbekov in 'Hanbook of Accelerator Physics and Engineering", edited by A. W. Chao and M. Tigner, World Scientific, 1999.

[6] Varian Vacuum Products Lexington, 121 Hartwell Avenue, Massachusetts, 02173 USA.

[7] M. K. Sullivan, "A Method for Calculating Pressure Profiles in Vacuum Pipes", SLAC, 1993.

[8] K. Gounder, "The Status of Run II at Fermilab", in the 2002 proceedings of ICHEP, Amsterdam, July 2002.

Appendix: A Simple Approach to Gas Pressure Profile

The general differential equation for relating pressure p, linear conductance c, linear pumping speed s and linear outgassing rate q is given by:

$$\frac{d}{dz}(c\frac{dp}{dz}) - sp + q = 0$$

Consider a beam line having periodic pumps with pumping speed s and separated by length L. The length of each pump l along the beam line is small compared to L or $l/L << 1$ and can be neglected. Then the linear conductance c of the beam line can be treated as uniform or at least piecewise uniform. Therefore, the above equation can be written in between pumps as:.

$$\frac{d^2p}{dz^2} + q/c = 0$$

We also require by symmetry that the pressure must be same at the pumps, i.e, $p(0) = p(L)$. The general solution to the above equation is:

$$p(z) = \frac{-q}{2c}z^2 + az + b$$

In steady state situations, the total outgassing rate Q = qL should be equal to gas pumped out (mass conservation):

$$Q = qL = p(0)s = p(L)s$$

This implies:

$$p(z) = \frac{-q}{2c}z^2 + az + \frac{qL}{s}$$

Now using the boundary condition p(0)=p(L), we obtain:

$$p(z) = \frac{-q}{2c}z^2 + \frac{qL}{2c}z + \frac{qL}{s}$$

Now by symmetry, the maximum pressure will be at the midpoint, z = L/2 and the minimum pressure will be at the pumps, z = 0 and at z = L.

$$p(0) = p(L) = \frac{qL}{s} \qquad --> minimum$$

$$p(L/2) = \frac{qL^2}{8c} + \frac{qL}{s} \qquad --> maximum$$

Note that $p(L/2) - p(0) = qL^2/8c$ is independent of pumping speed s! So we can compute the average pressure between pumps as:

$$< p >= \int_0^L dz \frac{p(z)}{L} = \frac{qL^2}{12c} + \frac{qL}{s}$$